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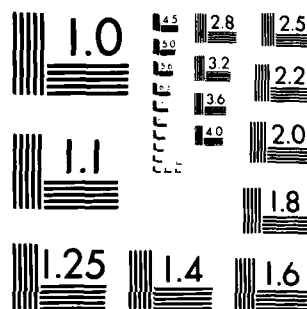
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FINAL REPORT

DYNAMIC RESPONSE OF VERTEBRAL ELEMENTS

by

J. F. LAFFERTY

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UNIVERSITY OF KENTUCKY

LEXINGTON, KY 40506

WENNER-GREN AERONAUTICAL RESEARCH LABORATORY

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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER AFOSR-TR. 88-0140	2. GOVT ACCESSION NO. 88-0140	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) DYNAMIC RESPONSE OF VERTEBRAL ELEMENTS		5. TYPE OF REPORT & PERIOD COVERED FINAL 1 JAN 78 - 31 DEC 82
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) J. F. Lafferty, D. A. Bowman		8. CONTRACT OR GRANT NUMBER(s) AFOSR 78-3488
9. PERFORMING ORGANIZATION NAME AND ADDRESS Wenner-Gren Research Laboratory Biomedical Engineering Center University of Kentucky, Lexington, KY 40506		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 61102F 2312/A2
11. CONTROLLING OFFICE NAME AND ADDRESS Air Force Office of Scientific Research Building 410 (NL) Bolling AFB, D.C. 20332		12. REPORT DATE 83 Jan 31
		13. NUMBER OF PAGES 24
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE
16. DISTRIBUTION STATEMENT (of this Report) Approved for public release; distribution unlimited.		
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)		
18. SUPPLEMENTARY NOTES		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) Intervertebral Disc, Stress, Viscoelastic Model		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) Creep response and relaxation data, obtained from shear, torsion, and compressive stress tests of the intervertebral disc, are used to develop an analytical model. A series chain of four Kelvin units was found to provide an excellent representation of the viscoelastic properties of the material; this model led to the development of two-element model with a time dependent viscous coefficient. The two element model characterizes the mechanical properties of the intervertebral disc in a concise representation suitable for computer utilization.		

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DYNAMIC RESPONSE OF VERTEBRAL ELEMENTS

PROGRAM OBJECTIVES

This report presents the results of a project undertaken to determine the mechanical response of the primate lumbar spine to applied stress and to represent that response mathematically.

INTRODUCTION

Knowledge of the response of the intervertebral joints to external loads is important if the forces and moments developed in the spine are to be related quantitatively to possible modes of injury or abnormal motions of the joint. A recent evaluation of biodynamic modeling by von Gierke [1] suggests that there is a critical need for experimental data for spinal deformations other than longitudinal.

Numerous investigators have studied the response of the spinal column and its constituent elements under axial tension and compression, in torsion, and in bending. Those who have considered the response to shearing deformations have limited their work to specific aspects of the shear response. For a concise review of past studies, see Lin, Liu, and Adams [2].

Markolf [3] studied the shearing displacement of the disc as a function of applied transverse shear force and examined the stiffness of the lumbar discs. His preliminary tests indicated that the posterior elements had no measurable influence upon the pure shear displacement of the intervertebral joint. He found the shear stiffness was much greater than that of any other mode

of deformation, with initial static shear stiffness ranging from 1050 to 5100 N/cm. Although the specimens were subjected to incremental loadings, no creep was observed in either the anterior-to-posterior or lateral shear tests. Markolf did not reduce his data to a stress-strain relationship, therefore no meaningful comparisons among levels or subjects could be made.

Liu, Ray, and Hirsch [4] outlined a method for the optimal estimation of the orthotropic material constants of the gross disc from experimentally measured values, with particular emphasis on the shear modulus of the disc along the anteroposterior and lateral directions. By the direct shear method, using specimens composed of two vertebrae and the intervening disc, the overall load-deflection characteristics of the intervertebral joint in shear were determined in the A-P and lateral directions. A three-dimensional model of the joint was constructed, taking into account the disc cross section and other geometric parameters. The model indicated that deflection of the segment was predominantly controlled by the shear deformation of the disc. The shear modulus, G , was the most sensitive material property, followed by Young's modulus, E . The values of G obtained ranged from 0.41 to .077 Kp/mm² (402.07-755.11 N/cm²); the values of E ranged from 0.53 to 1.16 Kp/mm² (519.75-1137.57 N/cm²). The number of specimens was too small to draw any statistical conclusions about possible correlations between material properties and spinal level or age of the cadaver.

Lin, Liu, and Adams [2] studied the mechanical behavior of lumbar intervertebral joints subjected to complex loading

(combined axial, shear, and bending), with particular emphasis on the role of the posterior elements during different loading situations. Their results, obtained from incremental loadings, were of the same magnitude as those of Markolf. In contrast to Markolf, they did observe creep during the test, and found that removal of the posterior elements reduced the shear stiffness. The lateral shear stiffness was generally higher than the anteroposterior shear stiffness, as it was in the studies of Liu, Ray, and Hirsch [4], Lin, Liu, and Adams did not reduce their data to a stress-strain relationship, thus no comparisons among levels or subjects were made.

The conflicting results in the work of Markolf [3] and that of Lin, Liu, and Adams [2] concerning the role of the posterior elements and the creep response during shearing deformation indicate the need for further investigation. Also, the role of the nucleus pulposus and the stress-strain characteristics of the intervertebral disc require quantification if analytical models are to provide realistic response data. This study was, therefore, undertaken to investigate these phenomena.

METHODS and MATERIALS

The same general procedures were used for tests of shear, torsion and compression response of the intervertebral disc. Test specimens consisting of two adjacent vertebrae and the intervening intervertebral disc were taken from fresh frozen Rhesus monkey lumbar spines. The anterior and posterior longitudinal ligaments were left intact across the disc space.

Tests were conducted at approximately 22 C and the specimens were kept moist with saline during the testing procedure. The specimens were held in the test fixture by clamps and by a metal rod inserted into the neural canal. Epoxy was used to mate the contour of the vertebral body to the fixture in order to minimize stress concentrations and bending moments, and to provide maximum stability.

The shear force was applied by an electrohydraulic system under the direction of a microcomputer. A hydraulic actuator and electronic controller formed the closed loop electrohydraulic system with either the applied force or the resulting displacement as the control variable. The relative motion between the two vertebrae was measured by a DCDT displacement transducer and was recorded versus time. The force, measured by an Interface 500 force transducer, was recorded as a function of time.

After testing, each specimen was frozen in a cellulose medium and 100 μ thick frontal sections were taken using a PMV cryomicrotome. Disc contours were digitized for every fifth to tenth section. With the aid of integrating routines, gross disc properties such as average disc height, total disc volume, and endplate areas were determined from the digitized data. These data were then used to compute accurate stress-stain data from the force-deflection measurement.

THEORETICAL CONSIDERATIONS

The stress-strain properties of viscoelastic materials are often represented by a series of Kelvin units as shown in Fig. 1. Analysis of this mechanical model provides an analytical model of strain as a function of stress in terms of the viscous and elastic parameters (constants). A fit of the analytical model to experimental data permits determination of the values of the parameters. This procedure is greatly facilitated by the use of "creep studies" in which the material is subjected to a step input of stress which is maintained constant for the duration of the test. Analysis of the model gives the creep function response as

$$\epsilon/\sigma = \frac{1}{k_3} + \frac{t}{c_3} + \frac{1}{k_1} [1 - \exp(-k_1 t/c_1)] + \frac{1}{k_2} [1 - \exp(-k_2 t/c_2)] \quad (1)$$

where ϵ = strain = deformation/disc height

σ = stress = force/disc area

t = time

k and c are constants

The structure of the intervertebral disc is such that any mode of applied stress is resisted by the annulus fibers in tension and the nucleus pulposus in compression. The form of Equation (1) should, therefore, be applicable for all stress modes although the value of some parameters will change. For tension, compression and shear the appropriate equation would be Equation (1). For torsional stress the parametric dependence is the same but the creep function must be defined in terms of torsion. The analysis of the shear response of an elastic

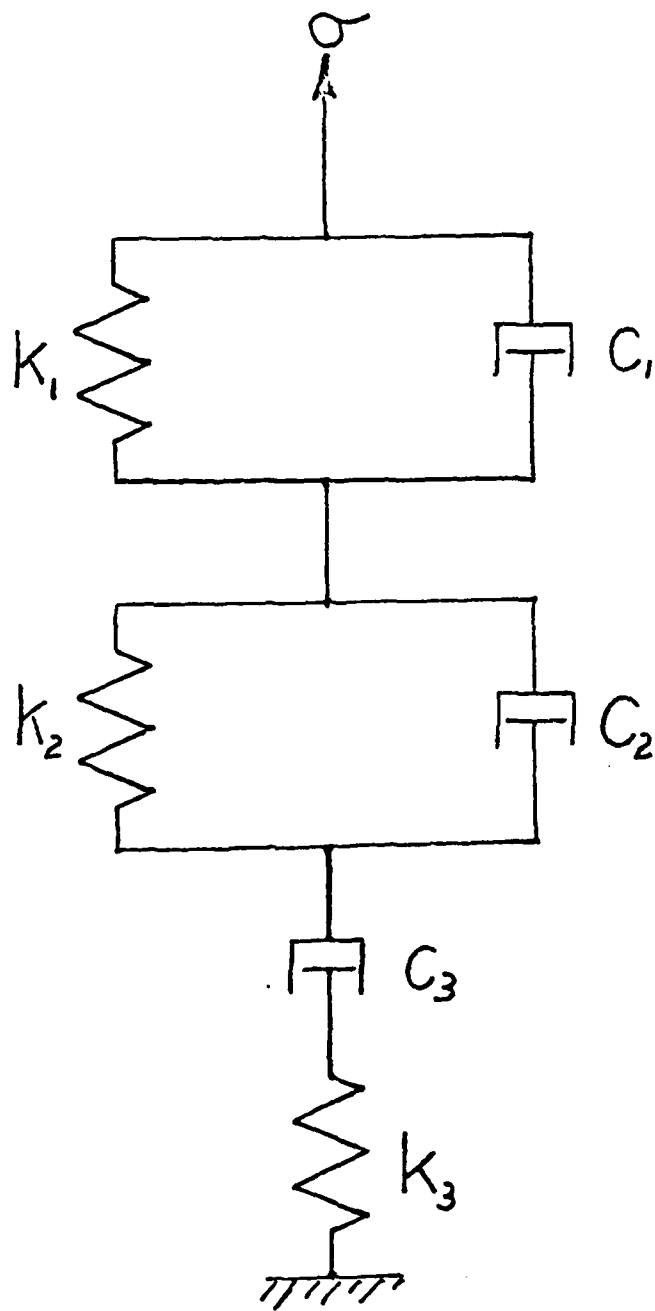


Fig. 1. Kelvin-Maxwell Series Model

isotropic material defines the shear modulus G as

$$\epsilon/\sigma = \frac{1}{G} \quad (2)$$

The analysis of the same material subjected to torsional stress shows that

$$\frac{\theta J}{TH} = \frac{1}{G} \quad (3)$$

where $\theta J/TH$ is the torsional equivalent ϵ/σ and

θ = angular deformation in radians

J = polar moment of inertial of cross sectional area (m^4)

T = applied torque ($N \cdot m$)

H = specimen height normal to the plane of the applied moment (m)

Although the intervertebral joint is a complicated structure that is neither purely elastic nor isotropic, some degree of correspondence between shear response and torsional response (as indicated by Equations 2 and 3) is expected.

RESULTS and DISCUSSION

1. Shear Stress

Two types of tests were conducted: force distribution and stress-strain characteristics. In the force distribution series, each of nineteen specimens was submitted to two tests. In the initial test, the intact specimen was stressed, at a rate of 32 N/s, until failure of the articular processes or to a maximum of 423 N. The facets were then removed and the disc stressed to failure. The two recordings were used to determine, for a given displacement, the percentage of applied force carried by the disc and that carried by the facets. The force carried by the

articular processes (with the disc intact), F_f , for a given displacement, is determined to be:

$$F_f = F_r - F_d$$

where F_r is the total applied force and F_d is the force carried by the disc after removal of the facet joints. The force required to fracture articular processes corresponds closely to the ultimate shear strength of the disc itself. Failure occurs at approximately 840 N with 3.5 mm displacement at facet failure and 6 mm displacement at disc failure. At facet failure the disc carries about 75 percent of the load (630 N), indicating that the facets alone would fail at about 210 N. Failure of specimens occurs by bilateral fracture of the articular processes followed by separation of the disc endplate from the vertebral body and tearing of the ligaments. The line of separation of the end-plate generally follows the junction of the epiphyseal plate and the metaphysis. Normally failure leaves the disc unit (annulus fibrosus, nucleus pulposus, and endplates) intact. In two cases, however, the disc itself failed, with rupture of the annulus and herniation of the nucleus. The herniation occurred dorsolaterally as is often the case in the in-vivo rupture ("slipped disc") in humans.

The percentage of the shear force carried by the disc (in the intact specimen), F_d , is shown as a function of the total force, F_r , in Fig. 2. The data indicate that at very low values of F_r , the disc sustains more than 40 percent of the load. The disc force decreases rapidly to a minimum of 0.34 F_r as F_r increases to 100 N. This characteristic is thought to reflect

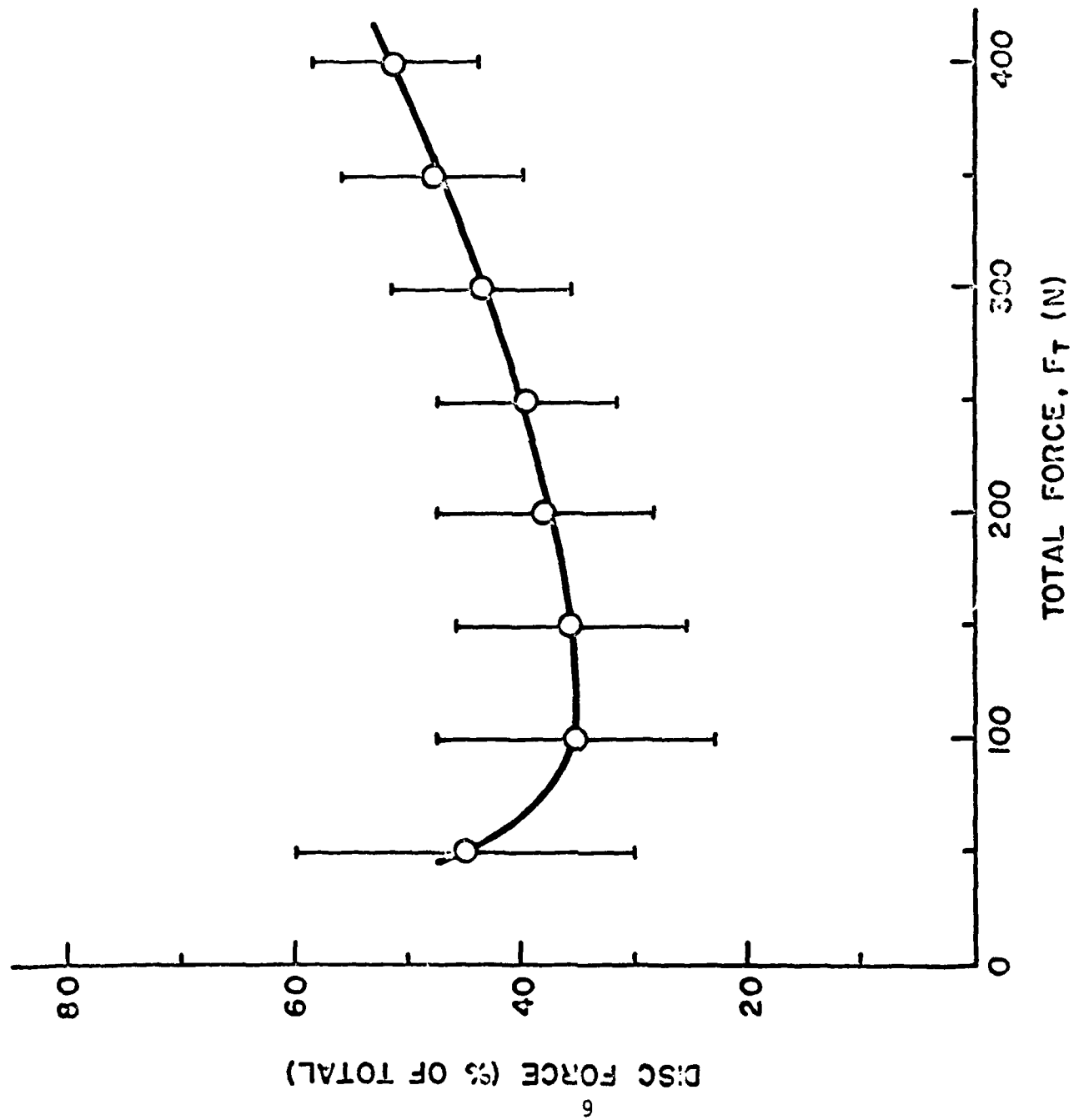


Fig. 2. Shear Force Carried by the Intervertebral Disc as a Percent of the Total

the relaxed state of the facet joints at zero load; as the load is increased to 100 N, the articular processes rapidly assume a greater fraction of the load. For values of F_r greater than 100 N, the disc force increases from 0.34 F_r to 50-65 percent of F_r at facet failure. At that point the disc assumes the full load and experiences a substantial increase in deflection before failure occurs.

In the stress-strain series, a second group of 15 specimens was tested with the articular processes removed. A shearing force of 200 N was applied at a rate of 32 N/s. The nucleus pulposus was extracted with a 17-gage needle (1.55 mm O.D.), and the test repeated. The force-deflection recordings were reduced to stress-strain data by dividing the force by the disc cross-sectional area and by dividing the deflection by the mean disc height.

The stress-strain characteristics of the intervertebral disc are illustrated in Fig. 3. When the nucleus pulposus is removed, the decreased disc height and relaxation of the annular fibers result in a greatly increased strain at low levels of stress. For stress levels greater than 20 N/cm², the shear modulus ($G = d\sigma/d\epsilon$) is nearly the same as that of the normal intact disc. A least squares fit to the linear portion of the curves given $G = 154.69 \pm 6.29$ N/cm² for the normal disc and $G = 169.88 \pm 7.73$ N/cm² for the enucleate disc. The fact that the moduli do not differ greatly in value would seem to indicate that the viscoelastic characteristics of the disc are due to the annular fibers, not to the nucleus. Also shown in Fig. 3 is the stress-

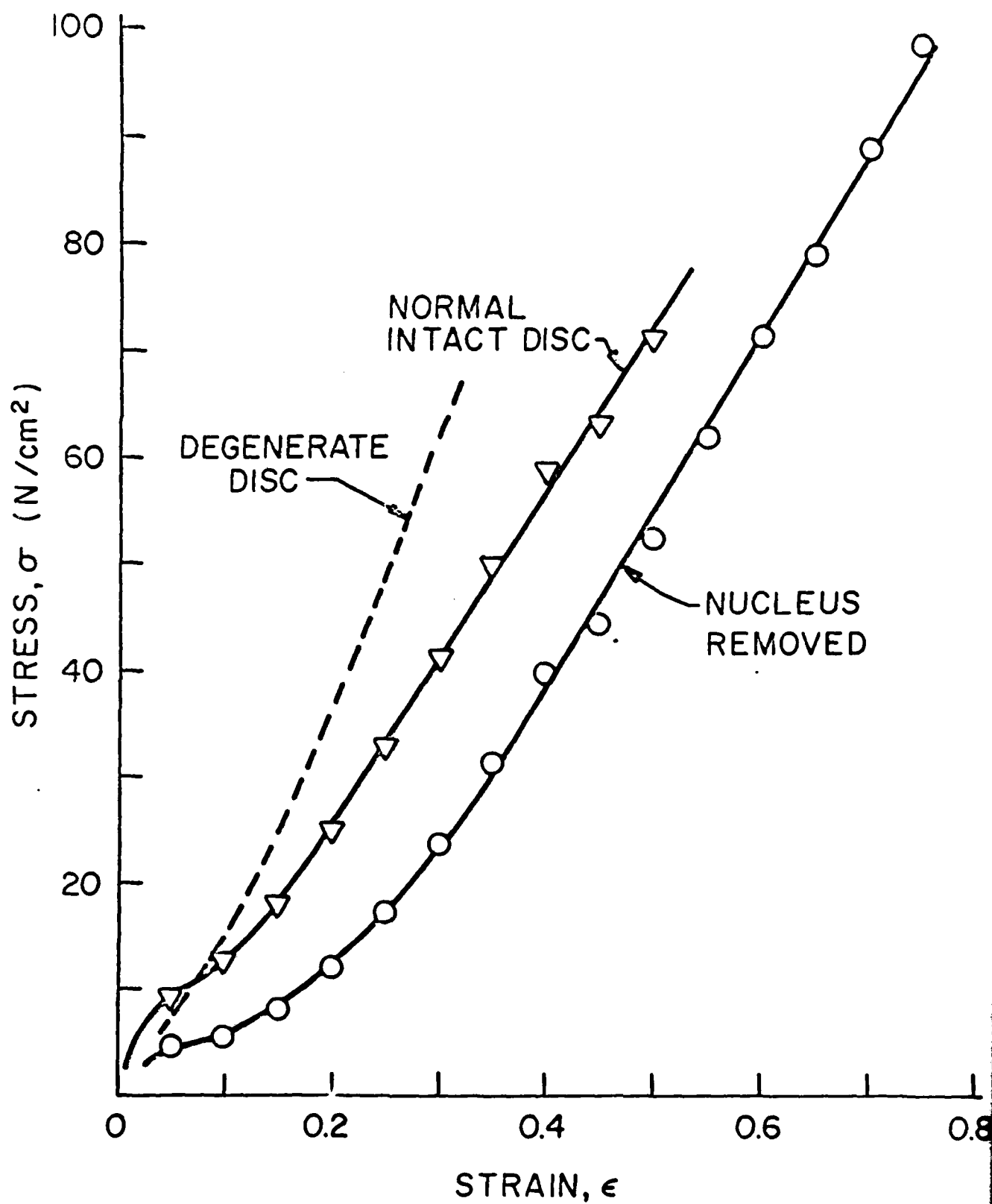


Fig. 3. Stress-Strain Characteristics of the Intervertebral Disc Subjected to Shear

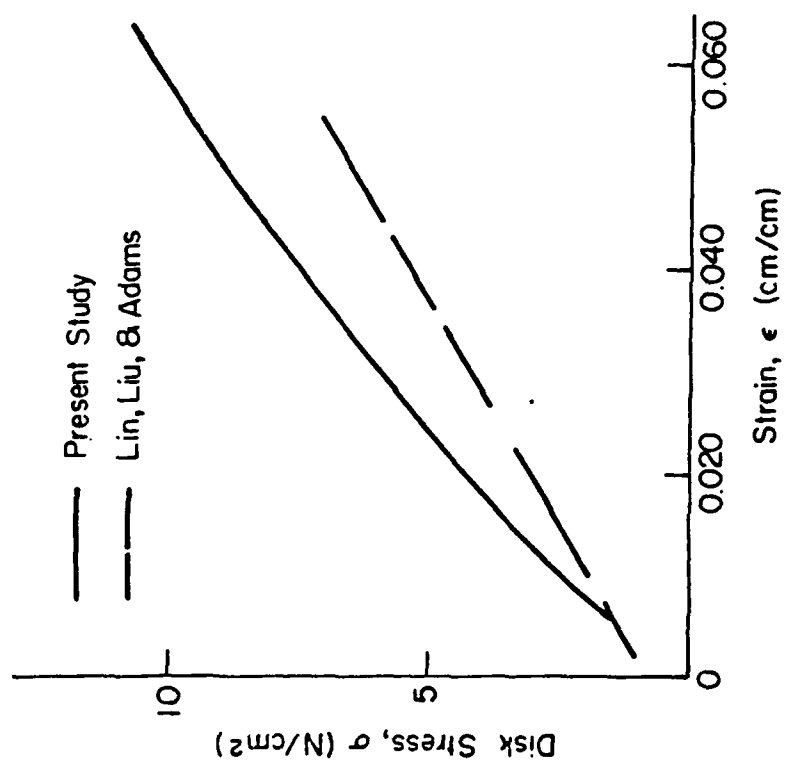


Fig. 4. Comparison of Human and Rhesus Data

strain response of the intact discs of a degenerate spine (group 4). A least squares fit to the linear portion of this curve gives $G = 180.22 \pm 5.70 \text{ N/cm}^2$.

Although Lin, Liu, and Adams [2] did not reduce their data to stress-strain, it was possible to obtain such a relationship since they listed the disc cross-sectional areas and mean disc heights of the specimens in their paper. Fig. 4 compares the stress-strain characteristics of the Rhesus intervertebral discs to those of the human specimens of Lin, Liu, and Adams. The disc stress of the human specimens, for a given strain, is lower than that of the Rhesus specimens. It should be noted, however, that the strain range is very small, and that this is a region of limited confidence for the data of the present study.

Creep tests were performed on thirteen specimens, each of which was submitted to constant stress at levels of approximately 20, 40, 80 and 160 N/cm^2 for 60 s. The creep displacement was recorded at each stress level. The relaxation test used fourteen specimens. Each specimen was subjected to strain levels of approximately 0.2, 0.4, 0.6 and 0.8 cm/cm. Specimens were in no way mechanically conditioned prior to either creep or relaxation testing. Each specimen was allowed to recover for at least two minutes between subsequent loadings. The stress was computed as the ratio of force to disc cross sectional area; strain was defined as the ratio of shearing deformation to disc height. The force required to create the specified stress level (creep test) was computed from the disc cross sectional area estimated from the areas of the discs immediately above and below the level

being tested. The displacement required for a specified strain (relaxation test) was computed from the disc height estimated from radiographs of the specimen. Accurate values of the stresses and strains were obtained from post test measurements of disc heights and disc areas. These data were used to obtain stress-strain values from which the creep function and relaxation function were computed. It was found that a minimum of four Kelvin units were required to accurately represent these data. The use of Kelvin units to aid in describing the experimental results allows this type of analysis to fall into the normal framework of the linear theory of viscoelasticity used by most authors to relate stress and strain. Noting that the initial response to a step stress of the intervertebral disc appeared to be elastic, the viscosity coefficient in one of the Kelvin units was assumed to be sufficiently small so that it could be considered negligible, leaving a series spring. Also, since the creep response appeared to approach a linear relationship in the time frame considered, the shear modulus of a second Kelvin unit was assumed to be sufficiently small as to be considered negligible resulting in a series dashpot.

The resulting equation

$$\epsilon/\sigma = 0.000575 [(1 - \exp(-1.3t)) + (1 - \exp(-0.13t))] + 0.00512 + 0.001t \quad (4)$$

represents the data with an average error of 0.33 percent. While the series spring and series dashpot are essential elements to the model in order to accurately describe the initial and 60 s responses of the intervertebral disc, any attempt to combine

these elements to anything less than a Kelvin unit (parallel spring and dashpot) would not demonstrate the viscoelastic responses observed. It was determined from computer modeling that the series spring and series dashpot combined in series with only one Kelvin unit could not represent these data over the time frame considered with an error of less than 3 percent. A comparison of creep function data to Equation (4) is presented in Fig. 5. The Kelvin parameters obtained from the creep function data were used to derive an analytical expression for the relaxation function from Equation (2). This equation

$$\sigma/\epsilon = 20.2 \exp(-1.45t) + 16.0 \exp(-0.143t) + 159 \exp(-0.00162t) \quad (5)$$

agrees with the data within an average error of 1.35 percent (Fig. 6), thus verifying the applicability of the Kelvin parameters obtained from the creep function data.

2. Torsional Stress

The vertebrae were clamped in holding fixtures with the superior vertebra constrained to prevent angular displacement about the spinal axis but free to move in the longitudinal direction. The torque was applied to the inferior vertebra by a MTS Servoram controlled by the Cromemco microprocessor. The torque was applied as a step function in increments of 1.875 Newton-meters up to failure. The creep response was observed for 90 seconds at each value of torque and the specimen was allowed to relax for a minimum of 180 seconds between tests. One series of tests (8 specimens) was conducted with an axial load of 12.945N and a second series (6 specimens) employed an axial load

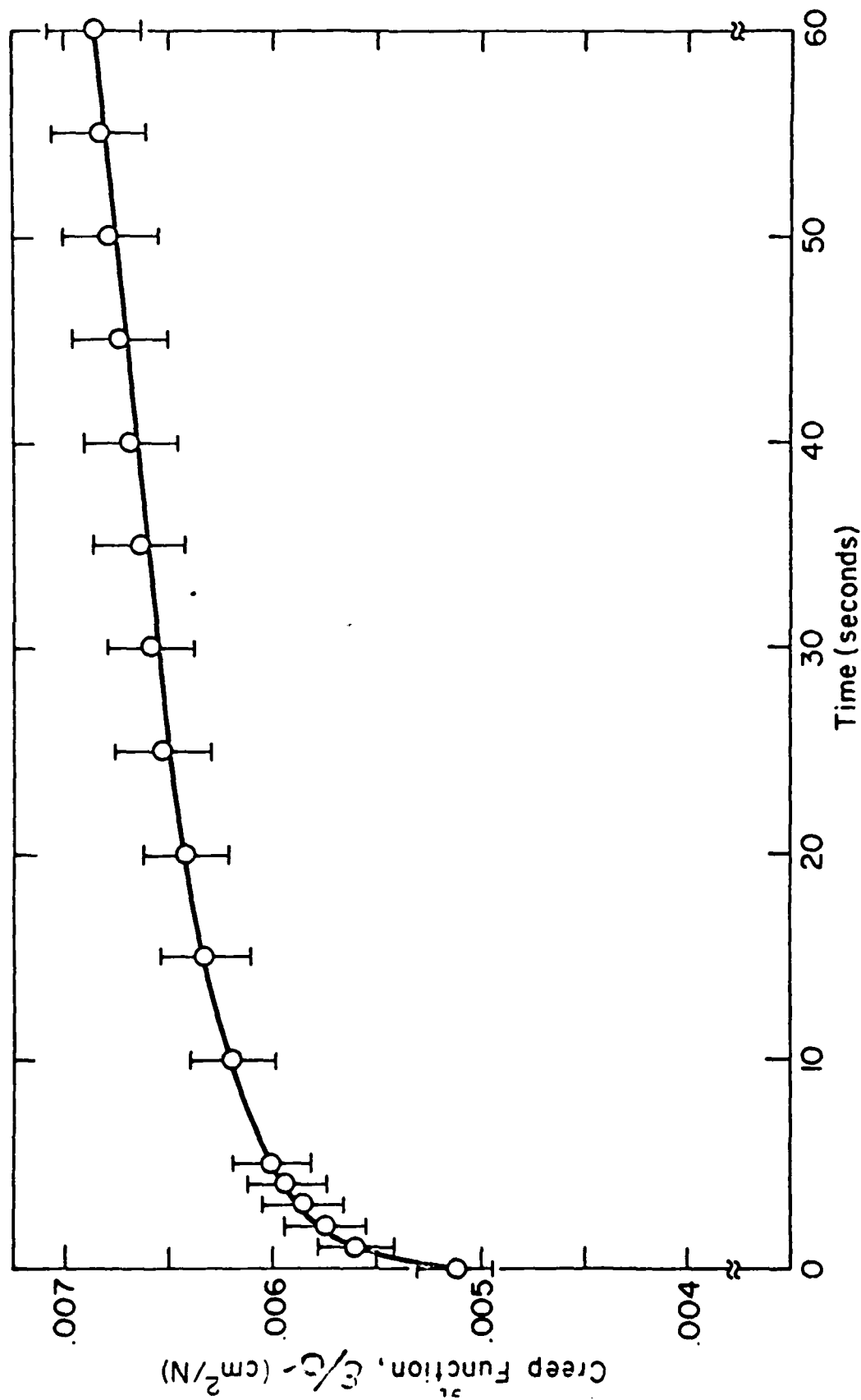


Fig. 5. Creep Function vs. Time for Shear Response

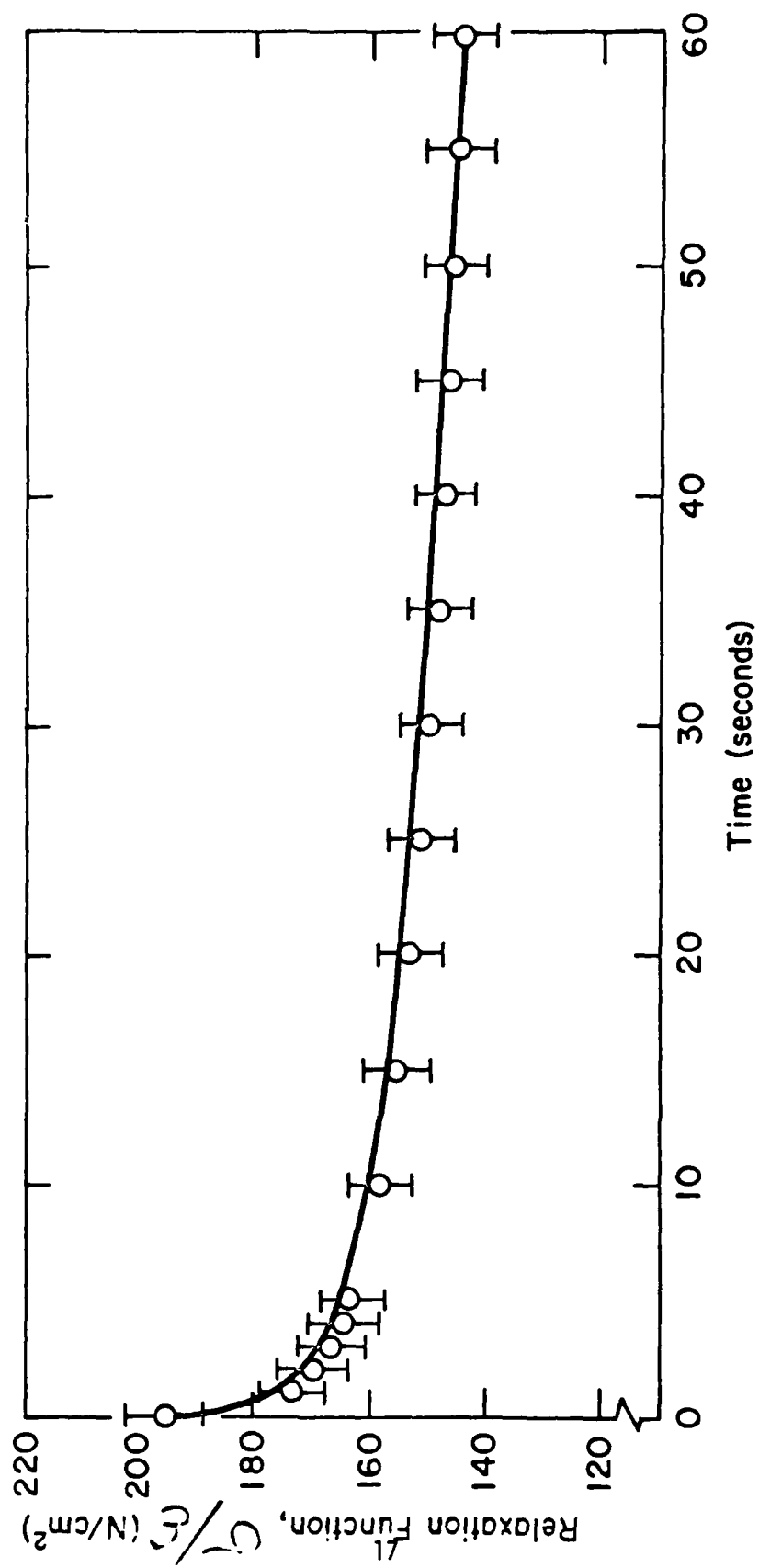


Fig. 6. Relaxation Function

of 27.66N. The geometrical data (disc height, disc area and volume) were obtained by sectioning each specimen in the frontal plane and using a Talos digitizer to record the coordinates of the disc.

The average values of $\theta J/TH$ displayed a standard deviation on the order of $\pm 35\%$ of the mean. We concluded that the imposition of the specific axial load to specimens obtained from subjects of widely varying size and weight contributed to the magnitude of the standard deviation. The creep modulus was, therefore, divided by the axial load expressed as a percent of body weight of the donor. This procedure reduced the standard deviation of the low level axial load data to 22%. However, standard deviation of the high level axial load data increased to 42%. The creep function is then defined as

$$K = \frac{\theta J}{THW} \quad (6)$$

where $W = (\text{axial load/body weight}) \times 100$

Use of the model in the form of Equation 1 provided a representation of the results to within $\pm 1\%$ of the averaged data. These results are presented graphically in Fig. 7 for the two levels of axial preload.

3. Compressive Stress

The compression tests used the same fixtures and procedures as the shear studies except that the stress was applied along the spinal axis. Creep test were performed on each of four specimens, with and without facets, and the results for each case used to evaluate the model. The model again was able to represent the data to within one percent of the mean of the

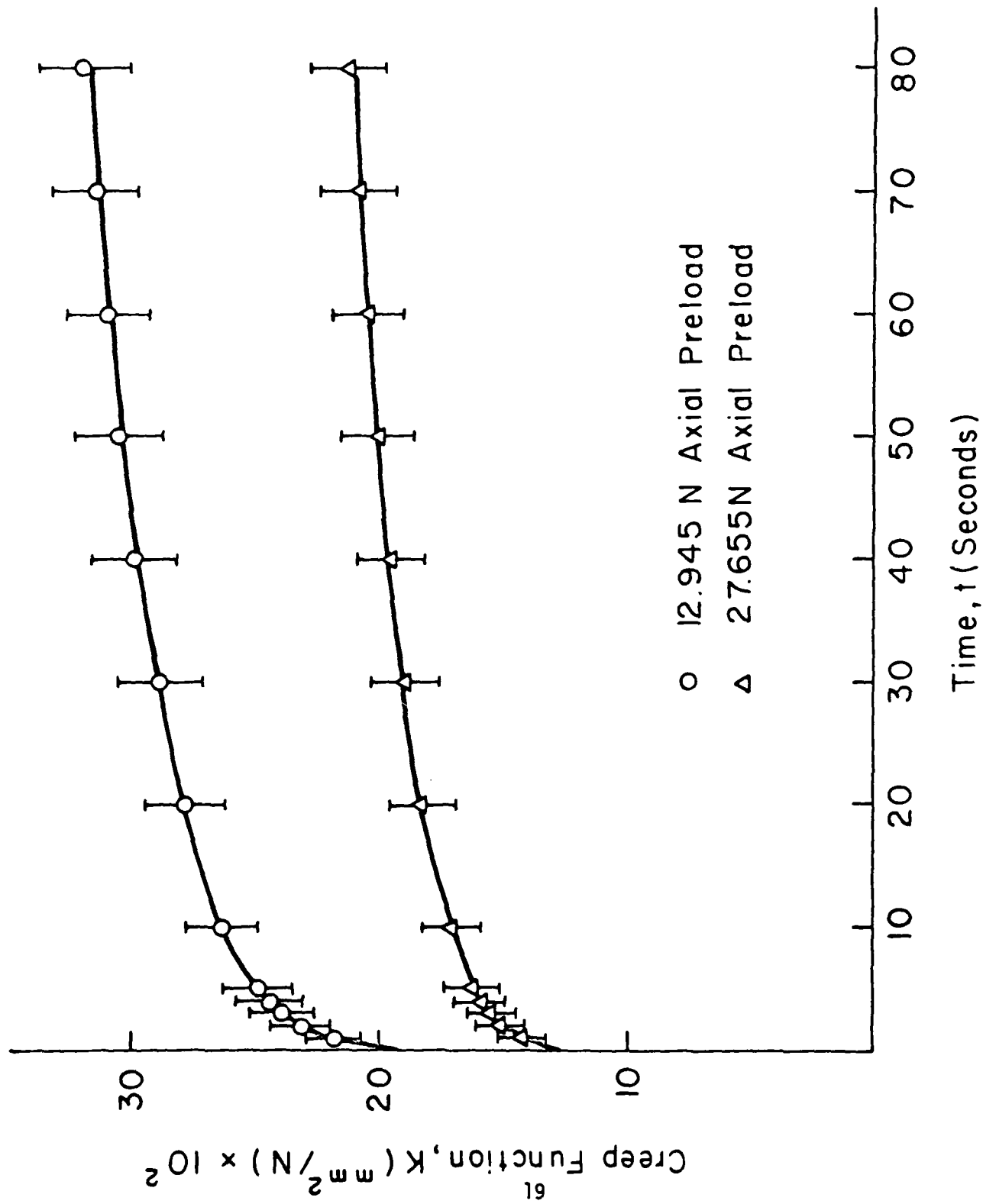


Fig. 7. Torsional Creep Function Illustrating Preload Effects

experimental data.

In this application of the model, as in previous applications, increased response time requires an increase in the number of Kelvin units necessary to accurately represent the data. This characteristic suggests that the viscous coefficient is a time dependent parameter. The nature of the creep response suggests that a simple two-element model of the form illustrated in Fig. 8 might approximate the observed response. Analysis of this model gives the creep response as:

$$\frac{1}{G} = \frac{1}{k} + \frac{t^{(1-\beta)}}{A(1-\beta)} \quad (7)$$

where G is as defined as the ratio of stress to strain for shear and compressive loading and is the deflection-torque ratio for torsional stress (see Equation 3). It was found that values of the three constants k, β , and A could be selected such that Equation 7 represents the data to within one percent of the experimental mean for each case (shear, torsion, compression). A comparison of model parameters for the three cases is presented in Table 1.

TABLE 1. MODEL PARAMETERS

	k	A	β
Compression	227.79	810.24	0.9065
Shear	2.677	42.669	0.874
Torsion	7.1023	68.306	0.817

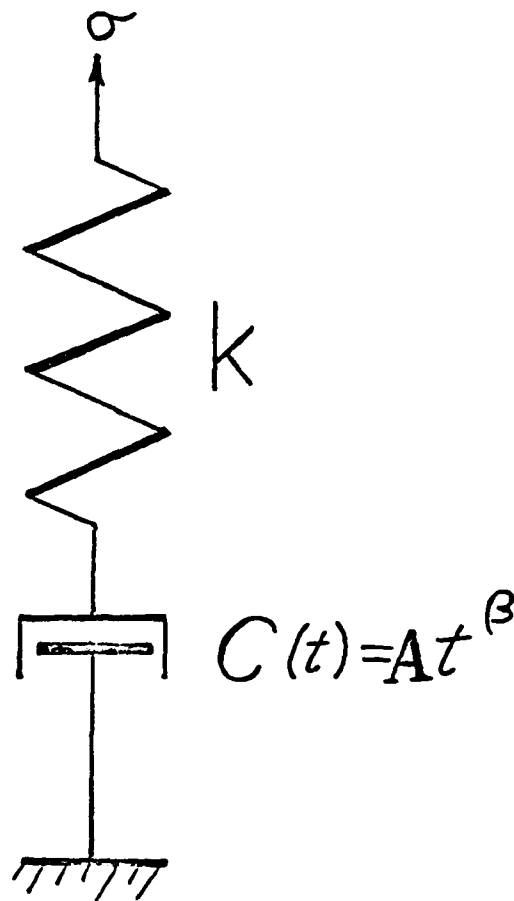


Fig. 8. Two-Element Model with Time Dependent Viscous Coefficient

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PRESENTATIONS

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"Torsional Stress-Strain Characteristics of the Rhesus Lumbar Spine," Lafferty, J. F. and Bowman, D. A. Presented at the First Southern Biomedical Engineering Conference, Shreveport, Louisiana, June 1982.

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